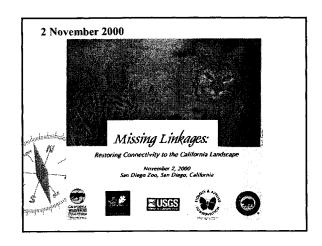
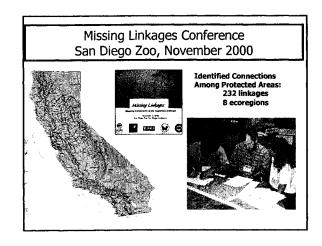
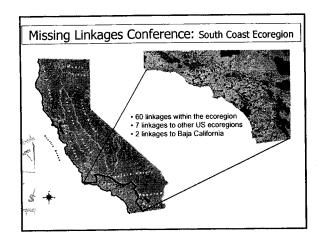
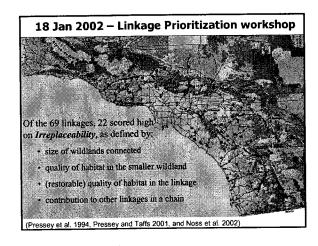
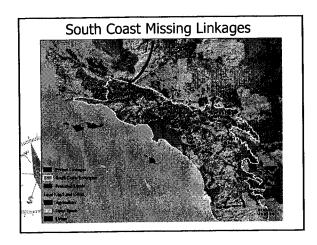
# South Coast Missing Linkages Project – restoring connectivity to southern California Kristeen Penrod, Clint Cabañero, Paul Beier, Wayne Spencer, Claudia Luke, Esther Rubin (and numerous others)

















### **Select Focal Species**

- Umbrella species (area-sensitive, sensitive to barriers)
- Range of vagilities & habitat affinities
- Species that need corridors AND species that the corridor needs.

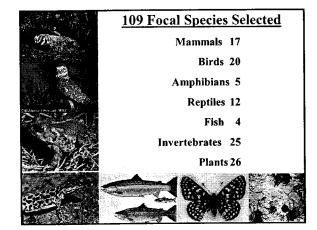


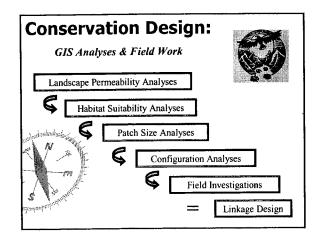
Focal Species Approach (Beier & Loe 1992)

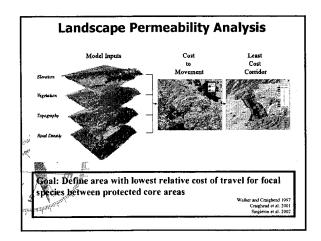
Steve Loe San Bernardino NF

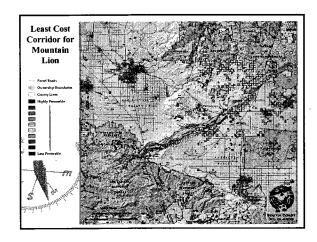
> Paul Beier SCWP & NAU

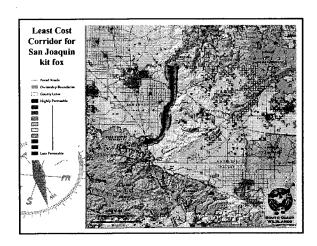


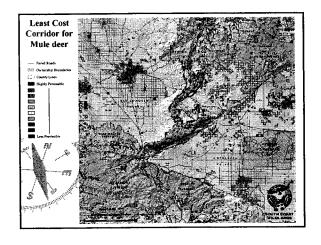


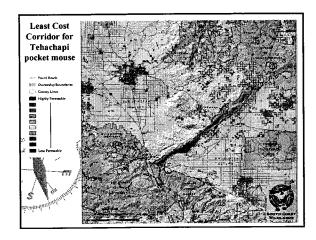


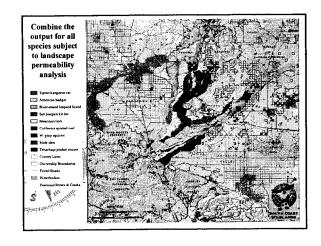


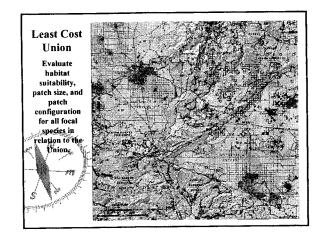


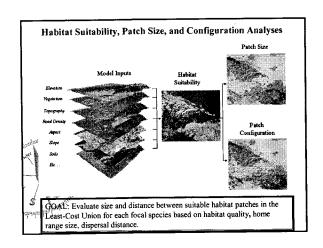


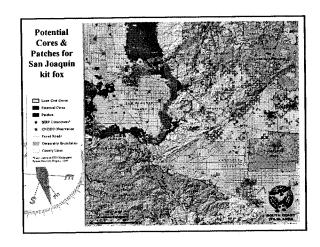




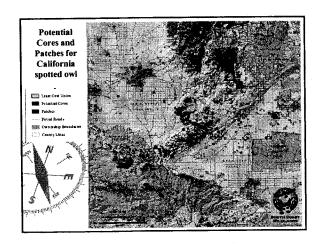


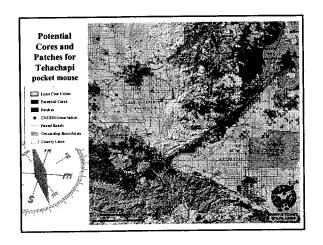


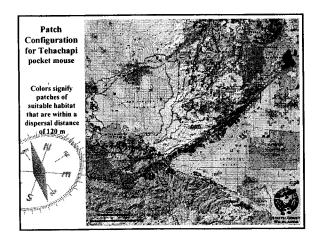


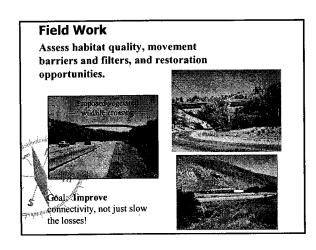


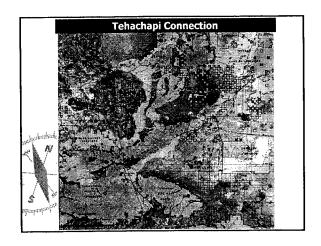












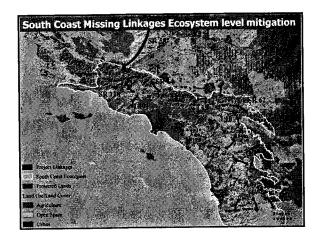
### Goals of Each Linkage Design:

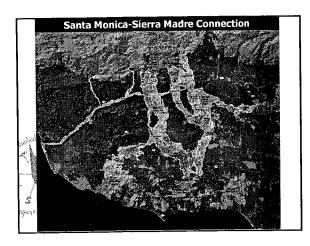
- Provide live in and move through habitat for multiple species.
- Support metapopulations of smaller species
- Ensure the availability of key resources
- Buffer against edge effects

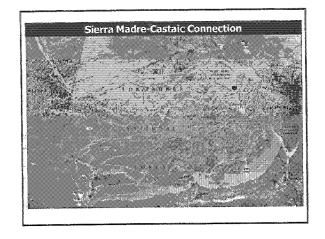
Allow natural process to operate

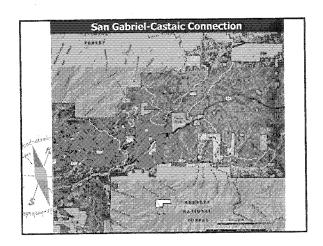
Allow species and communities to respond to climatic changes

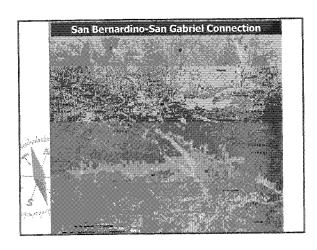


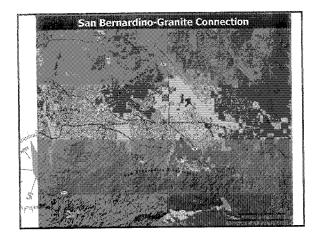


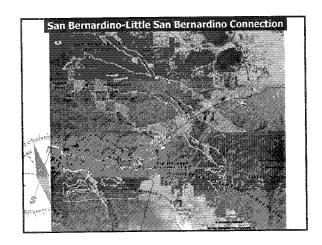


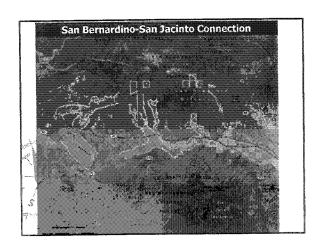




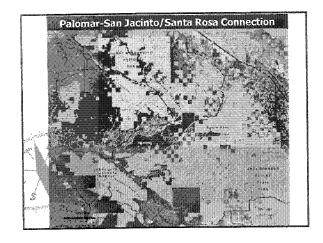


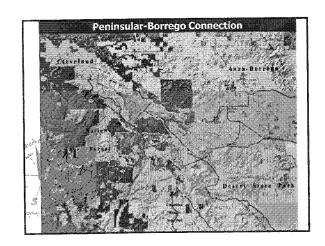


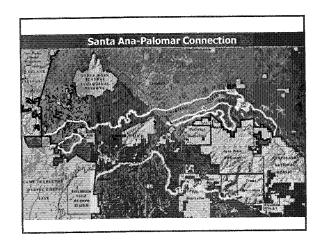


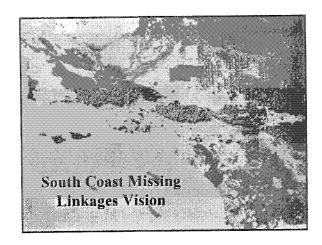


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### Project Status:

- Communications Plan for Unveiling SCML vision.
- Results being actively incorporated into conservation plans by numerous partners and planning entities
- Approach being exported to other regions and states, including

  Arizona

  New Mexico

  Colorado



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Car	Conclusion: Collaboration Works!		
For more information: www.scwildlands.org			
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# Attachment D: "Missing Linkages" Studies in the SCAG Region\*

\*Prepared by Paul Beier, Ph.D. For copies of the "Missing Linkages" reports, go to <a href="https://www.scwildands.org">www.scwildands.org</a>.

### California Missing Linkages

Species that once moved freely through a mosaic of natural vegetation types are now confronted with a man-made labyrinth of barriers, such as roads, homes, businesses, and agricultural fields that fragment formerly expansive natural landscapes. Movement patterns crucial to species survival are being altered rapidly. To counter these trends, California has initiated a systematic approach for identifying, protecting, and restoring functional connections across the landscape to allow essential ecological processes to continue operating as they have for millennia.

In November 2000, a coalition of conservation and research organizations (California State Parks, California Wilderness Coalition, The Nature Conservancy, Zoological Society of San Diego's Center for Reproduction of Endangered Species, and U.S. Geological Survey) launched a statewide interagency workshop at the San Diego Zoo entitled "Missing Linkages: Restoring Connectivity to the California Landscape". The workshop brought together over 200 land managers and conservation ecologists representing federal, state, and local agencies, academic institutions, and non-governmental organizations to identify "potential linkages" – that is, areas where natural connectivity is at risk. Of the 232 potential linkages identified at the workshop (Figure 1), 69 were associated with the South Coast Ecoregion and 46 were associated with the Mohave and Sonoran Deserts Ecoregion of southern California (Penrod et al. 2001).

Many of these potential linkages fall within the SCAG region (Figure 2) and are limited in several ways:

- Some important potential linkages may not have made it to the map. With no formal way to exhaustively list core areas, some possible pairs of core areas needing connectivity may not have been noticed.
- The potential linkages vary greatly in importance. For example, a potential linkage between 2 small, highly degraded wildlands is less important than a potential linkage between 2 large, intact wildlands.



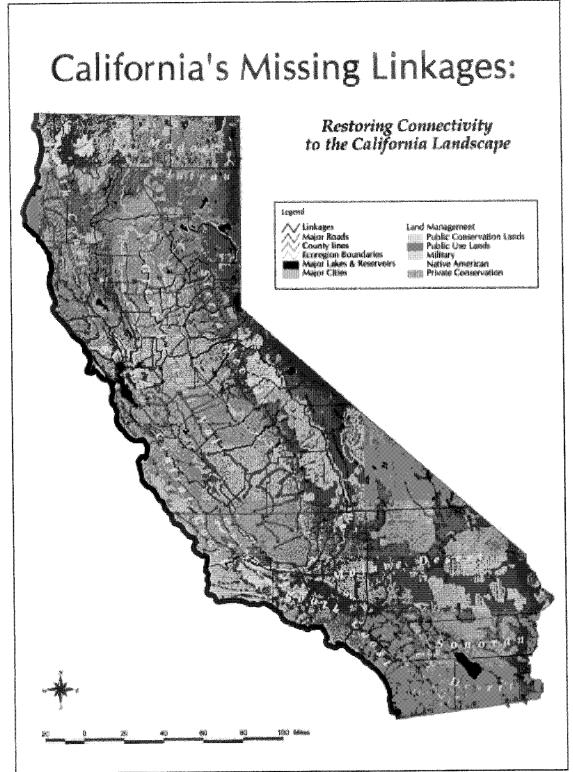


Figure 1. California Missing Linkages Map



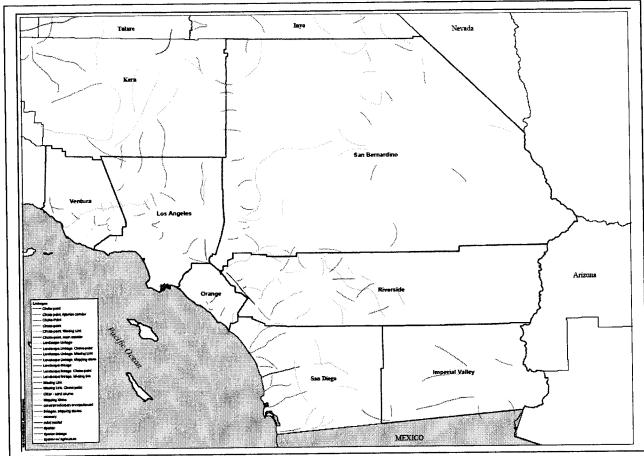


Figure 2. Potential linkages in and near the SCAG Region.

- Some potential linkages may have been permanently obstructed by human development at the time they were put on this list. Others may become obstructed since 2000.
- In some cases what was perceived as one core area in 2000 may now be perceived as 2 core areas delineated by potential barriers (roads, urbanization) that arose since 2000.

For these reasons, we offer a procedure for identifying core areas and potential linkages among them. Nonetheless the potential linkages indicated on the map form a useful reference list for SCAG by indicating areas where, in the opinion of experts familiar with this landscape, wildlife connectivity was both important and threatened.



### **Prioritizing Potential Linkages**

Following the statewide Missing Linkages conference, South Coast Wildlands, a nonprofit organization established to pursue habitat connectivity planning in the South Coast Ecoregion, brought together regional ecologists to conduct a formal evaluation of 69 linkages in the South Coast Ecoregion, most but not all of which fall in the SCAG region. The evaluation was designed to assess the biological irreplaceability and vulnerability of each linkage (sensu Noss et al. 2002). Irreplaceability assessed the relative biological value of each linkage, including both terrestrial and aquatic criteria: 1) size of habitat blocks served by the linkage; 2) quality of existing habitat in the smaller habitat block; 3) quality and amount of existing habitat in the proposed linkage; 4) linkage to other ecoregions or key to movement through the ecoregion; 5) facilitation of seasonal movement and responses to climatic change; and 6) addition of value for aquatic ecosystems. Vulnerability was evaluated using recent high-resolution aerial photographs, local planning documents, and other data concerning threats of habitat loss or fragmentation in the linkage area. This process identified 16 linkages of crucial biological value that are likely to be irretrievably compromised by development projects over the next decade unless immediate conservation action occurs; eleven of these linkages fall in the SCAG region (Figure 3).

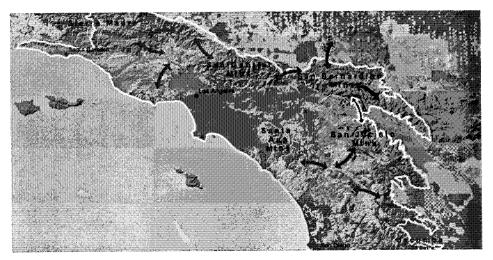


Figure 3. Eleven Priority South Coast Ecoregion Linkages within the SCAG Region

From northwest to southeast the linkages are between:

- Sierra Madre Mountains and Castaic Ranges
- San Gabriel Mountains and Castaic Ranges,
- Santa Susana Mountains and Sierra Madre Mountains
- Santa Monica Mountains and Santa Susana Mountains



- San Bernardino Mountains and San Gabriel Mountains
- San Bernardino Mountains and Granite Mountains
- San Bernardino Mountains and Little San Bernardino Mountains
- San Bernardino Mountains and San Jacinto Mountains (highlighted in figure)
- Palomar Ranges and San Jacinto/Santa Rosa Mountains
- Santa Ana Mountains and Palomar Ranges,
- Peninsular Ranges and Anza Borrego

Note that the South Coast Ecoregion only partially overlaps the SCAG region. Thus these may not be the 11 most important linkages in the much larger SCAG region. The primary reason for mentioning these linkages is because detailed linkage designs exist for these 11 areas (see below).

### Linkage Designs for 11 Potential Linkages in the SCAG Region

Identification of these priority linkages launched the South Coast Missing Linkages Project. This project is a highly collaborative effort among federal and state agencies and non-governmental organizations to identify and conserve landscape-level habitat linkages to protect essential biological and ecological processes in the South Coast Ecoregion. Partners include: South Coast Wildlands, The Wildlands Conservancy, The Resources Agency California Legacy Project, California State Parks, California State Parks Foundation, United States Forest Service, National Park Service, Santa Monica Mountains Conservancy, Rivers and Mountains Conservancy, Conservation Biology Institute, San Diego State University Field Stations Program, The Nature Conservancy, Southern California Wetlands Recovery Project, Environment Now, Mountain Lion Foundation, and the Zoological Society of San Diego's Conservation and Research for Endangered Species. Cross-border alliances have also been formed with Pronatura, Universidad Autonoma de Baja California, and Conabio.

South Coast Wildlands coordinated and hosted regional workshops, provided resources to these partners, and conducted GIS analyses for the 11 priority linkages. These 11 plans are available on the South Coast Wildlands website (www.scwildlands.org/), or by request from Kristeen Penrod or Paul Beier. Each report contains several common elements that may be of use to SCAG:

• Ecological Significance of the Linkage: A description of the biological resources in each core area connected by the linkage, and in the potential linkage area, highlighting rare or special-status species and biotic communities.





- Existing Conservation Investments: A list of the publicly-owned and privatelyconserved wildlands that would be linked by a functioning corridor, with an
  emphasis on Wilderness Areas, National Parks or Monuments, and other areas
  managed predominantly for biological values.
- A list of focal species used to design the linkage. In each linkage area, 12-30 species were selected to represent the entire biotic community and ecological processes. Each linkage design is thus intended to be comprehensive.
- A map of the linkage design. The linkage is typically composed of 2-5 strands or braids, rather than being a single narrow band connecting the core areas. For instance the perennial streams may be joined in a long non-linear strand to serve fish, amphibians, and water-dependent species. A second band might consist of flat scrub and desert grassland to serve species like badgers and jackrabbits. A third strand might be dominated by rugged topography for species such as bighorn sheep. Each strand is broad to buffer against edge effects, such as weed invasion, artificial night lighting, predation by house pets, increases in opportunistic species like raccoons, elevated soil moisture from irrigation, pesticides and pollutants, noise, trampling, and domesticated animals that attract native predators. Width also reduces the risk that fires, floods, and other natural processes might affect the entire linkage simultaneously.
- A summary of land ownership, land cover, and topography in each strand of the linkage design.
- A description and photographs of major threats to wildlife movement, and specific recommendations to mitigate those barriers. These mitigation measures include recommendations for particular types of highway crossing structures at particular locations on major roads, canals, or railroads, recommendations for controlling urbanization, and recommendations for streams.
- A list of land protection and stewardship opportunities in the linkage design.

These reports can be used in the SCAG project to provide (a) detailed information on particular wildlife linkages, and/or (b) a template to ensure that future linkage designs provide similar information, or even more useful types of information.

# Attachment E: Analytic Tools for Avoiding, Reducing, and Mitigating Impacts

to Wildlife Linkages from Transportation Projects\*

\*This document is a working draft prepared by Paul Beier, Ph.D.

The impacts of roads<sup>1</sup> on wildlife are diverse (Spellerberg 1998, Forman & Alexander 1998, Forman et al. 2003). In this document, we ignore impacts due to pollution (from combustion, de-icing agents, construction materials), loss of habitat due to the area occupied by the road or urban growth induced by the road, exotic plant species that spread from rights-of-way into wildlands, edge effects due to noise & artificial night lighting, and indirect impacts due to altered hydrology and increased erosion near the road. Although these impacts can be substantial, here we focus on how roads impact the ability of wildlife to move between the remaining wildlands on either side of the road (Table 1).

Table 1. Impacts of roads on wildlife corridors and wildland connectivity, with appropriate mitigations for various types of impacts.

Impact	Appropriate Mitigations	
barrier to within-population movement		
barrier to recolonization	• crossing structures	
barrier to gene flow	conserve habitat leading from each crossing structure to remaining wildlands	
barrier to seasonal migration		
barrier to ecological processes such as pollination, seed dispersal, predator-prey interactions, nutrient cycling, and shifting geographic range in response to climate change.	As above, but habitat corridor must be broad and must contain diverse soils & topography to enable entire communities to shift.	
mortality due to collisions with vehicles	roadside fencing (must be integrated with crossing structures)	

The main significant impacts of roads on wildlife linkages are several types of barrier effects and direct mortality of animals attempting to cross the road:

- Barrier to within-population movement: When a formerly large area of habitat is dissected by roads, it may become impossible for individual animals to move across the road between the remaining wild areas. Thus a 1000-acre area may become two 500-acre areas isolated from each other, and each wildlife population becomes two, smaller, populations. These small areas may be too small to support a population of some wildlife species. The impact is particularly severe for area-sensitive species that is, species that need a large area to support a population, such as mountain lions, bears, deer, bighorn, badgers, and other large and medium-sized mammals. As a result, populations become demographically unstable and eventually become extinct in each patch.
- Barrier to recolonization: Species may become extinct in local areas for a variety of reasons. If migrants can re-colonize the area by moving from nearby habitat, extinction will be temporary. However roads can preclude such recolonization.
- Barrier to gene flow: Until recently, most scientists believed it would take at least a century for roads to cause measurable genetic divergence in wildlife populations, especially for long-lived species in which genetic change occurs slowly. However, 2 recent studies, both conducted in the SCAG region, provide the first scientific evidence that 40- to 50-year-old highways profoundly decrease gene flow in large mammals, namely bighorn sheep (Epps et al. 2005) and bobcats and coyotes (Riley et al. 2006).
- Barrier to seasonal movement: In the SCAG region, probably only a few large
  mammal populations migrate between wintering and summer areas. Where such
  migration occurs, it is critically important that highways have vegetated overpasses or
  bridged undercrossings to allow mammals to migrate (Berger 2004). Although many
  birds in the SCAG region migrate, migratory birds can fly across unsuitable habitat
  and are probably not affected by highways.
- Barrier to ecological processes such as pollination, seed dispersal, predator-prey
  interactions, and nutrient cycling, and shift of geographic range: Of these processes,
  the ability of animals and natural communities to shift their geographic range is of
  particular importance, because range shift it the only way (other than extinction) that
  species and natural communities can respond to climate change. Mitigation for this
  type of barrier effect will requires a broad linkage.

<sup>1</sup> We use the term "road" or "highway" as shorthand for any linear transportation project, including freight rail, high-speed rail, and aqueducts in addition to highways.





• Mortality of animals attempting to cross roads: Severe impacts have been documented on the cougar in southern California, the Florida panther, the ocelot, the wolf, and the Iberian lynx (Forman et al. 2003). In a 4-year study of 15,000 km of road observations in Organ Pipe Cactus National Monument, Rosen and Lowe (1994) found a minimum of 22.5 snakes per km per year killed due to vehicle collisions. Using a more frequent monitoring in an area of high turtle density, Aresco (2005) found 11.9 turtles killed per km per day along a 4-lane highway in Florida. This impact can be addressed by fencing that prevents an animal from entering the roadway, which can reduce mortality of animals by 80% to 99% (Clevenger et al. 2001a, Dodd et al. 2004, Aresco 2005). However, fencing alone is not a satisfactory solution because it increases the barrier effects listed above – unless the fencing is integrated with other types of mitigations (such as highway crossing structures and conservation of land in the linkage).

The impacts listed above can be avoided, minimized, and mitigated by 2 types of mitigation (Table 1, Table 2), namely crossing structures integrated with roadside fencing, and conserving habitat between crossing structures and affected wildlands. Although there are few scientific studies documenting the effectiveness of underpasses and overpasses in facilitating wildlife movement, there is a clear pattern emerging from those studies, such that it is possible to propose a set of best management practices for crossing structures. GIS tools are needed to identify lands to conserve in the vicinity of road crossing structures (Table 2).

Table 2. The two main types of mitigation for transportation projects

Type of Mitigation	Notes	
Crossing structures integrated with roadside fencing	A cookbook set of best management practices (diversity of structures, with 300m spacing between small structures, 1 mile spacing between large structures, design guidelines for structures) is sufficient when a road bisects protected wildland (i.e., habitat is already conserved).	
Conserve habitat leading from each crossing structure to remaining wildlands	If developable land occurs in the wildlife linkage, GIS analysis can identify which land to conserve. To date, most such GIS analyses have concerned particular focal species, but it is better linkages to serve multiple species and to accommodate ecologic processes, such as the ability of species to shift their range in response to climate change.	

### **Best Management Practices for Road Crossing Structures**

Wildlife crossing structures that have been used in North America and Europe to facilitate movement through landscapes fragmented by roads include wildlife overpasses & green bridges, bridges, culverts, and pipes (Figure 1). While many of these structures were not originally constructed with ecological connectivity in mind, many species benefit from them (Clevenger et al. 2001; Forman et al. 2003). No single crossing structure will allow all species to cross a road. For example rodents prefer to use pipes and small culverts, while bighorn prefer vegetated overpasses or open terrain below high bridges. A concrete box culvert may be readily accepted by a mountain lion or bear, but not by a deer or bighorn sheep. Small mammals, such as deer mice and voles, prefer small culverts to wildlife overpasses (McDonald & St Clair 2004).

Wildlife overpasses are most often designed to improve opportunities for large mammals to cross busy highways. Approximately 50 overpasses have been built in the world, with only 6 of these occurring in North America (Forman et al. 2003). Overpasses are typically 30 to 50 m wide, but can be as large as 200 m wide. In Banff National Park, Alberta, grizzly bears, wolves, and all ungulates (bighorn sheep, deer, elk, and moose) prefer overpasses to underpasses, while species such as mountain lions prefer underpasses (Clevenger & Waltho 2005).

Wildlife underpasses include viaducts, bridges, culverts, and pipes, and are often designed to ensure adequate drainage beneath highways. For ungulates such as deer, tall, wide bridges are best. Mule deer in southern California only used underpasses below large spanning bridges (Ng et al. 2004) and the average size of underpasses used by white-tailed deer in Pennsylvania was 15 ft wide by 8 ft high (Brudin 2003). Because most small mammals, amphibians, reptiles, and insects need vegetative cover for security, bridged undercrossings should extend to uplands beyond the scour zone of the stream, and should be high enough to allow enough light for vegetation to grow underneath. In the Netherlands, rows of stumps or branches under crossing structures have increased connectivity for smaller species crossing bridges on floodplains (Forman et al. 2003).

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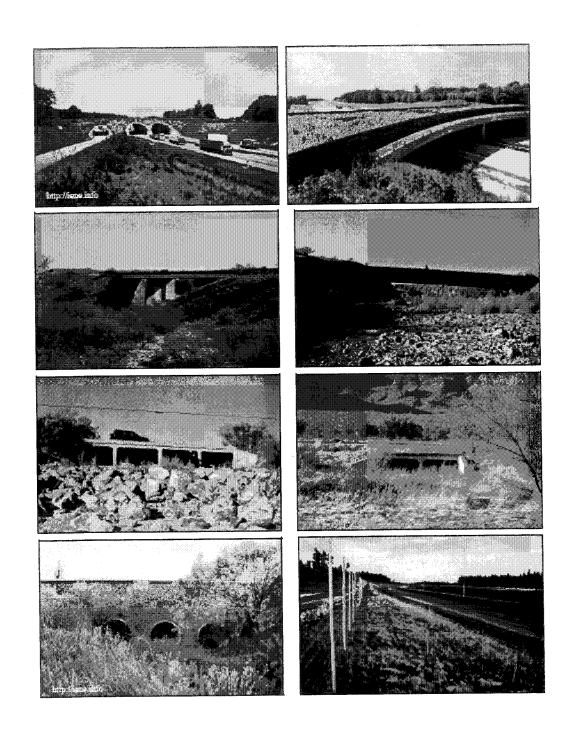


Figure 1. Potential road mitigations (from top to bottom) include: highway overpasses, bridges, culverts, and drainage pipes. Fencing (lower right) should be used to guide animals into crossing structures.



Drainage culverts can mitigate the effects of busy roads for small and medium sized mammals (Clevenger et al. 2001; McDonald & St Clair 2004). Culverts and concrete box structures are used by many species, including mice, shrews, foxes, rabbits, armadillos, river otters, opossums, raccoons, ground squirrels, skunks, coyotes, bobcats, mountain lions, black bear, great blue heron, long-tailed weasel, amphibians, lizards, snakes, and southern leopard frogs (Yanes et al. 1995; Brudin III 2003; Dodd et al. 2004; Ng et al. 2004). Black bear and mountain lion prefer less-open structures (Clevenger & Waltho 2005). In south Texas, bobcats most often used 1.85 m x 1.85 m box culverts to cross highways, preferred structures near suitable scrub habitat, and sometimes used culverts to rest and avoid high temperatures (Cain et al. 2003). Culvert usage can be enhanced by providing a natural substrate bottom, and in locations where the floor of a culvert is persistently covered with water, a concrete ledge established above water level can provide terrestrial species with a dry path through the structure (Cain et al. 2003). It is important for the lower end of the culvert to be flush with the surrounding terrain. Many culverts are built with a concrete pour-off of 8-12 inches, and others develop a pour-off lip due to scouring action of water. A sheer pour-off of several inches makes it unlikely that many small mammals, snakes, and amphibians will find or use the culvert.

Several sets of best management practices related to roads have been published recently (National Cooperative Highway Research Program 2004, Riverside County 2004, National Research Council 2005). There are only a few scientific studies to support these guidelines, and most designs are based on understanding of animal behavior with few data on efficacy of the design. However, the existing literature clearly suggests that almost any crossing structure will be useful to at least some wildlife species, that a variety of structures interspersed along a highway will be useful to many wildlife species, and that steep pour-offs and debris can ruin an otherwise useful structure.

In light of this consensus, the following 9 recommendations provide a set of best management practices that can be applied throughout the SCAG ecoregion. In an area where a road crosses wildland that is protected from development, following these guidelines should mitigate most of the road impact on wildlife movement. However the additional step of GIS analysis (next section) is necessary in areas where multiple roads have cumulative impacts, or developable land occurs between the road and protected wildlands.



- 1. Multiple crossing structures should be constructed at a crossing point to provide connectivity for all species likely to use a given area (Little 2003). Different species prefer different types of structures (Clevenger et al. 2001; McDonald & St Clair 2004; Clevenger & Waltho 2005; Mata et al. 2005). For deer or other ungulates, an open structure such as a bridge is crucial. For medium-sized mammals, black bear, and mountain lions, large box culverts with a natural earthen substrate flooring are optimal (Evink 2002). For small mammals, pipe culverts from 0.3m 1 m in diameter are preferable (Clevenger et al. 2001; McDonald & St Clair 2004). Maintain a height of 3 m and an appropriate openness ratio of at least 0.6 for crossings intended for use by mule deer; calculate this ratio as opening width x opening height/length of crossing (Riverside County 2004).
- 2. At least one crossing structure should be located within an individual's home range. Because most reptiles, small mammals, and amphibians have small home ranges, metal or cement box culverts should be installed at intervals of 150-300 m (Clevenger et al. 2001). For ungulates (deer, pronghorn, bighorn) and large carnivores, larger crossing structures such as bridges, viaducts, or overpasses should be located no more than 1.5 km (0.94 miles) apart (Mata et al. 2005; Clevenger and Wierzchowski 2006). Inadequate size and insufficient number of crossings are two primary causes of poor use by wildlife (Ruediger 2001).
- 3. Suitable habitat for species should occur on both sides of the crossing structure (Ruediger 2001; Barnum 2003; Cain et al. 2003; Ng et al. 2004). This applies to both *local* and *landscape* scales. On a local scale, vegetative cover should be present near entrances to give animals security, and reduce negative effects such as lighting and noise associated with the road (Clevenger et al. 2001; McDonald & St Clair 2004). A lack of suitable habitat adjacent to culverts originally built for hydrologic function may prevent their use as potential wildlife crossing structures (Cain et al. 2003). On the landscape scale, "Crossing structures will only be as effective as the land and resource management strategies around them" (Clevenger et al. 2005). Suitable habitat must be present throughout the linkage for animals to use a crossing structure.
- 4. Whenever possible, suitable habitat should occur within the crossing structure. This can best be achieved by having a bridge high enough to allow enough light for vegetation to grow under the bridge, and by making sure that the bridge spans upland habitat that is not regularly scoured by floods. Where this is not possible, rows of stumps or branches under large span bridges can provide cover for smaller animals such as reptiles, amphibians, rodents, and invertebrates; regular visits are needed to replace artificial cover removed by flood. Within culverts, earthen floors are preferred by mammals and reptiles.

- 5. Structures should be monitored for, and cleared of, obstructions such as detritus or silt blockages that impede movement. Small mammals, carnivores, and reptiles avoid crossing structures with significant detritus blockages (Yanes et al. 1995; Cain et al. 2003; Dodd et al. 2004). In the southwest, over half of box culverts less than 8 x 8 ft have large accumulations of branches, Russian thistle, sand, or garbage that impede animal movement (Beier, personal observation). Bridged undercrossings rarely have similar problems.
- 6. Fencing should never block entrances to crossing structures, and instead should direct animals towards crossing structures (Yanes et al. 1995). In Florida, construction of a barrier wall to guide animals into a culvert system resulted in 93.5% reduction in roadkill, and also increased the total number of species using the culvert from 28 to 42 (Dodd et al. 2004). Fences, guard rails, and embankments at least 2 m high discourage animals from crossing roads (Barnum 2003; Cain et al. 2003; Malo et al. 2004). In an area with no large animals, a 3-foot wall with an 18-inch lip projecting into the adjacent open space can direct small wildlife toward crossing structures (Riverside County 2004). One-way ramps on roadside fencing can allow an animal to escape if it is trapped on a road (Forman et al. 2003).
- 7. Raised sections of road discourage animals from crossing roads, and should be used when possible to encourage animals to use crossing structures. Clevenger et al. (2003) found that vertebrates were 93% less susceptible to road-kills on sections of road raised on embankments, compared to road segments at the natural grade of the surrounding terrain.
- 8. Manage human activity near each crossing structure. Clevenger & Waltho (2000) suggest that human use of crossing structures should be restricted and foot trails relocated away from structures intended for wildlife movement. However, a large crossing structure (viaduct or long, high bridge) should be able to accommodate both recreational and wildlife use. Furthermore, if recreational users are educated to maintain utility of the structure for wildlife, they can be allies in conserving wildlife corridors. At a minimum, nighttime human use of crossing structures should be restricted.
- 9. Design culverts specifically to provide for animal movement. Most culverts are designed to carry water under a road and minimize erosion hazard to the road. Culvert designs adequate for transporting water often have pour-offs at the downstream ends that prevent wildlife usage. At least 1 culvert every 150-300m of road should have openings flush with the surrounding terrain, and with native land cover up to both culvert openings, as noted above.

### GIS Procedures to Prioritize Conservation Land within a Linkage

Building a set of excellent highway underpasses and overpasses integrated with roadside fencing will not mitigate impacts to wildlife movement if the land between the highway and the nearest wildland is converted to urban uses or other uses incompatible with wildlife occupancy or movement. The goal of GIS analysis is to identify a continuous corridor of land which – if conserved and integrated with underpasses or overpasses across potential barriers – will best maintain or restore the ability of wildlife to move between large protected habitat blocks. Following Beier et al. (2006), we call this proposed corridor a *Linkage Design*.

Noss & Daly (2006) discuss alternative approaches to linkage design. At the low-tech end of the spectrum are what Noss and Daly call "seat of the pants" approaches. These approaches might involve selecting the only remaining route between 2 areas, the most direct route, the route with the largest parcels and willing sellers, the route that incorporates parcels of interest to investors, and a route based on the opinion of a species expert. All of these approaches can be appropriate and effective under some conditions. For instance, the Coal Canyon Biological Corridor, which was added to Chino Hills State Park in 2000, was the only remaining route between the Chino Hills and the Santa Ana Mountains for any wildlife species, and consisted of only 3 parcels. In this case, a seat of the pants approach was appropriate.

Noss and Daly also describe empirical an modeling approaches to linkage design; these are preferred to seat of the pants approaches when the length of the potential corridor is not fully constrained by existing urban barriers. If planners wish to conserve multiple focal species, GIS analyses such as least cost corridor analysis and spatially-explicit population models are the appropriate tools.

Like all models, GIS procedures involve uncertainty and simplifying assumptions, and therefore do not produce absolute "truth" but rather an estimate or prediction of the optimal wildlife corridor. Despite this limitation, there are several reasons to use models instead of maps hand-drawn by species experts or other intuitive approaches:

- 1. Developing the model forces important assumptions into the open.
- 2. Using the model makes us explicitly deal with interactions (e.g., between species movement mobility and corridor length) that might otherwise be ignored.
- 3. The model is transparent, with every algorithm and model parameter available for anyone to inspect and challenge.
- 4. The model is easy to revise when better information is available.

There are many GIS approaches that can develop a Linkage Design, but, except for the Least Cost Path tool in ArcGIS, there are no standardized, named approaches. Even the Least Cost Path tool assumes the analyst has developed a cost-surface layer, for which there is no standard approach. About 15 scientific papers – all published in the last 10





years – use GIS procedures to develop a Linkage Design (Walker & Craighead 1997, Quinby et al. 1999, Hoctor et al. 2000, Graham 2001, Servheen et al. 2001, Bani et al. 2002, Schadt et al. 2002, Singleton et al. 2002, Joly et al. 2003, Sutcliffe et al. 2003, Kramer-Schadt et al. 2004, Wikramanayake et al. 2004, Marulli and Mallarach 2005, Williams et al. 2005, Beier et al. 2006). However, each paper focuses on the resulting Linkage Design - the GIS procedures are never the main point of the paper. Indeed, no paper fully explains the many choices made during the analysis.

In Figure 2 we provide a flow chart illustrating most of the options involved in creating a GIS-based Linkage Design<sup>2</sup>. Some of the options are conceptually possible, but have not been put into practice. Other choices probably have little impact on the Linkage Design; however, except for Newell and Beier (In Prep), no published sensitivity analyses address how these choices affect the ultimate map. Here we briefly discuss the choices; the numbers below correspond to numbers in the flow chart (Figure 2).

1. Almost all studies estimate travel cost using literature review and expert opinion. There are potential alternatives, but to date they are untested and perhaps not feasible: (a) Gerlach and Musolf (2000) and Epps et al. (2005), respectively, used genetic analysis to estimate the travel cost of rivers on vole movement and of highways on bighorn movement. However, their analyses assumed that each pixel of matrix could be assigned to one of two cost classes (one for the river or highway, one for all other matrix pixels). Their approach would not yield unique estimates if the matrix were modeled as having multiple classes. (b) Travel cost could theoretically be measured from documented rates of interpatch movement (e.g., Sutcliffe et al. 2003). However if the landscape contains more than a handful of habitat classes, thousands of combinations of costs are consistent with the observed interpatch movement or genetic patterns (Sutcliffe et al. 2003). Furthermore, unless the researcher samples the entire geographic range of the species or metapopulation, estimates will be distorted due to (unmeasured) movements or gene flow from patches outside the study area but within the interacting group of patches. (c) Individual-based movement models are another promising alternative, but so far have been used only in a landscape with 150-m long corridors (Levey et al. 2005), and have not been used to estimate travel cost.

<sup>2</sup> This figure and much of the related discussion will form the basis of a paper in preparation by Beier and colleagues. Ovals indicate choices the analyst must make. Line 2 lists land cover, elevation, topography, and distance to roads (or road density) as the driving factors, but the analyst may use only a subset of these, or may add other factors if GIS coverage is available.



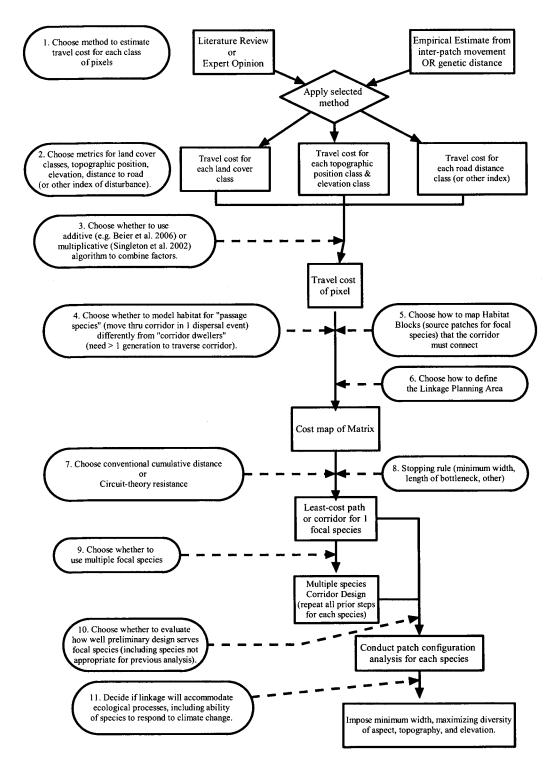


Figure 2. Generalized flow chart for GIS-based corridor design.



E-11



- 2. Typically, GIS models predict travel cost based on some or all of 4 factors: land cover (vegetation and land use classes), elevation, topography, and proximity to roads. Theoretically, one could use other factors but in practice, these are the only 4 widely-available GIS layers. Once the factors are selected, the analyst estimates the cost associated with each class using the method selected in #1. Newell and Beier (in prep) found that uncertainty in the cost estimates did not greatly affect the predicted best corridor of most species, but had an enormous impact for a few species.
- 3. The cost scores for land cover, elevation, proximity to roads, and topography can be combined as a weighted sum or a weighted product. The multiplicative model better reflects the possibility that one factor (e.g., proximity to roads) may limit wildlife movement in a way that cannot be compensated by a better score for another factor (e.g., land cover). Beier and Majka (Northern Arizona University, personal observation) find that this choice does not have a major impact on the Linkage Design.
- 4. Only Beier and colleagues (in 8 linkage designs produced for Arizona Game and Fish Department in 2006) have added a special procedure to model movement by species that require multiple generations to move through a corridor. Their procedure assigns an arbitrarily low travel cost to any group of contiguous pixels of sufficient quality and size to support breeding by the focal species. This procedure tends to produce a corridor that runs between steppingstones of breeding habitat, and substantially improves the Linkage Design. Although a similar improvement can be achieved via Patch Configuration Analysis (#10), recognizing the value of breeding patches early in the analysis is more efficient and less subjective.
- 5. The Linkage Design is profoundly affected by how the analyst delineates the habitat patches to be linked. The analyst might choose to have the linkage connect only to lands with the strongest conservation mandate, such as designated wilderness areas, Research Natural Areas, and Preserves managed by The Nature Conservancy. The analyst might also delineate habitat blocks to include National and State Parks, National Forest land, BLM land, military land, Bureau of Reclamation Land, and Native American reservations. There is no "right" answer to this issue but it seems reasonable that the areas to be connected should be likely to remain wild for at least 50 years. A closely related issue is whether the corridor for a single species should connect to any part of the protected habitat block (a common practice), or only to a large patch of suitable breeding habitat within the protected habitat. The latter seems more reasonable and involves relatively little additional work, and is standard on Linkage Designs produced by South Coast Wildlands and the Arizona Missing Linkages project at Northern Arizona University.



- 6. The GIS analyst cannot consider all possible travel paths on the planet, continent, or ecoregion, but is limited to a (usually rectangular) analysis area. Cumulative travel cost is calculated only for pixels within this Linkage Planning Area. As long as the Linkage Planning Area includes the boundary of each habitat block that "faces" the other habitat block and does not exclude any patches of high-quality habitat for the focal species, practitioners assume that this decision has little impact on the linkage design.
- 7. A circuit-theory resistance model was recently developed to model gene flow via multiple pathways (McRae, In Press), but has not yet been applied to Linkage Designs. It has some theoretical advantages and may become a useful tool in the future.
- 8. The swath of pixels with the lowest ecological cost is the best corridor for each species. However, the analyst must choose how wide the swath needs to be. The Least Cost Path tool in ArcGIS can identify a strand exactly one pixel wide between the habitat blocks clearly too narrow to serve most species. An arbitrary minimum width (say ¼ mile) seems attractive, but often exceptions must be made for existing bottlenecks, such as those created by existing urban areas. Regardless of what rule is selected to stop adding pixels to the corridor, this is a labor-intensive part of the process, as the procedure cannot be fully automated, but must be done interactively.
- 9. Thus far, the procedure produces a biologically-best corridor for a single species. In most cases, conservation planners will want to design a corridor to serve multiple species and ecological processes. Analyzing a southern California linkage designed using 8 focal species, Newell and Beier (in prep.) found that the single-species corridors for carnivores (mountain lion, badger, and kit fox) were not good umbrellas for the other 5 species there was no substitute for multi-species modeling if one wants to ensure connectivity for multiple species.
- 10. The GIS procedure will always produce a biologically best corridor even if the best corridor is entirely inadequate for the focal species. Some sort of spatially-explicit population model is needed to evaluate the biologically best corridor. Beier and colleagues developed "patch configuration analysis" as a relatively simple procedure for this purpose. The procedure basically maps patches of habitat of high quality (breeding) habitat large enough to support breeding pairs and small populations, and overlays these on the draft corridor design. The analyst evaluates these patches with respect to the species dispersal distance and the draft corridor design.

11. Impose a minimum width. Wide linkages are beneficial because they (1) provide adequate area for development of metapopulation structures necessary to allow corridor-dwelling species (individuals or genes) to move through the landscape; (2) reduce pollution into aquatic habitats; (3) reduce edge effects such as pets, lighting, noise, nest predation & parasitism, and invasive species; (4) provide an opportunity to conserve natural fire regimes and other ecological processes; and (5) improve the opportunity of biota to respond to climate change

## Illustration: Approach Used by South Coast Missing Linkages and Arizona Wildlife Linkage Workgroup

These 11 analytic decisions (Figure 2) can give rise to a very large number of alternative GIS approaches. One approach has been used by South Coast Wildlands and 25 partners in the South Coast Missing Linkages project to design 16 linkages in southern California during 2001-2006. This approach has been modified for use in 24 linkage designs in the state of Arizona by the Arizona Wildlife Linkage Workgroup during 2005-2008. We outline that approach in this section. To provide a consistent tense and minimize length, the description is written as a set of instructions (do this, then do this).

The approach uses GIS approaches to identify optimal travel routes for focal species representing the ecological community in the area. By carefully selecting a diverse group of focal species and capturing a range of topography to accommodate climate change, the Linkage Design should ensure the long-term viability of all species in the protected areas. The approach includes the following steps:

- 1. Select focal species.
- 2. Create a habitat suitability model for each focal species.
- 3. Join pixels of suitable habitat to identify potential breeding patches & potential population cores (areas that could support a population for at least a decade).
- 4. Identify the biologically best corridor (BBC) through which each species could move between protected core areas. Join the BBCs for all focal species.
- 5. Ensure that the union of BBCs includes enough population patches and cores to ensure connectivity for the focal species.
- 6. Expand the linkage to a minimum width.
- 7. Carry out field visits to identify barriers to movement and the best locations for underpasses or overpasses within Linkage Design area.



### **Focal Species Selection**

Use a focal species approach (Lambeck 1997) to represent the needs of the ecological community within the potential linkage area. Invite regional biologists familiar with the region to identify 10-20 species with one or more of the following characteristics:

- habitat specialists, especially habitats that may be relatively rare in the potential linkage area.
- species sensitive to highways, canals, urbanization, or other potential barriers in the potential linkage area, especially species with limited movement ability.
- area-sensitive species that require large or well-connected landscapes to maintain a viable population and genetic diversity.
- ecologically important species such as keystone predators, important seed dispersers, herbivores that affect vegetation, or species that are closely associated with nutrient cycling, energy flow, or other ecosystem processes.
- species listed as threatened or endangered under the Endangered Species Act, or species of special concern to Arizona Game and Fish Department, US Forest Service, or other management agencies.

Construct corridor models for some, but not all, focal species. Do not model species for which there are insufficient data to quantify habitat use in terms of available GIS data (e.g., some snakes that select small rocks), or if the species probably can travel (e.g., by flying) across unsuitable habitat.

### **Habitat Suitability Models**

Create habitat suitability models (Appendix A) for each species by estimating how the species responds to four habitat factors mapped at a 10x10m or 30x30 m level of resolution (Figure 3):

- Vegetation and land cover. Use the best seamless map available. If desired, merge some classes to create <50 vegetation & land cover classes.
- Elevation: the USGS National Elevation Dataset digital elevation model.
- *Topographic position*. Characterized each pixel as ridge, canyon bottom, flat to gentle slope, or steep slope.





• Straight-line distance from the nearest paved road or railroad. Distance from roads reflects risk of being struck by vehicles as well as noise, light, pets, pollution, and other human-caused disturbances. Either road density or distance to road can be used. There are problems with each.

To create a habitat suitability map, assign each of the 46 vegetation classes (and each of 4 topographic positions, and each of several elevation classes and distance-to-road classes) a score from 1 (best) to 10 (worst), where 1-3 is optimal habitat, 4-5 is suboptimal but usable habitat, 6-7 may be occasionally used but cannot sustain a breeding population, and 8-10 is strongly avoided. Whenever possible, recruit biologists with the greatest expertise in each species to assign these scores. If no expert is available for a species, three biologists independently assign scores and, after discussing differences among their individual scores, adjust their scores before the three scores are averaged. Regardless of whether the scores were generated by a species expert or project staff, the scorer should review the literature on habitat selection by the focal species before assigning scores<sup>3</sup>.

This scoring produces 4 scores (land cover, elevation, topographic position, distance from roads) for each pixel, each score being a number between 1 and 10. Then weight each of the 4 factors by a weight between 0% and 100%, subject to the constraint that the 4 weights must sum to 100%, and add the 4 weighted scores to produce an overall habitat suitability score, also scaled 1-10. Use these habitat suitability scores to create a habitat suitability map that form the foundation for the later steps.

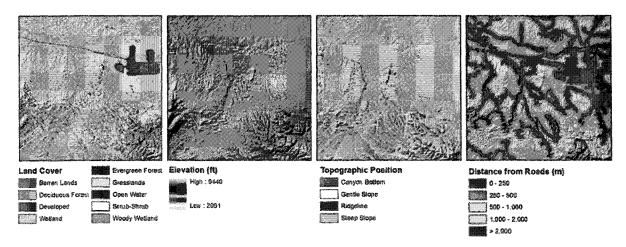


Figure 3: Four habitat factors used to create habitat suitability models. Inputs included vegetation, elevation, topographic position, and distance from roads.

<sup>3</sup> Clevenger et al. (2002) found that literature review significantly improved the fit between expert scores and later empirical observations of animal movement.

If necessary, use additional factors critical for a particular species, such as a minimum slope needed as escape terrain for bighorn sheep, or proximity to water for frogs. To create a habitat suitability model using critical features, reclassify any pixel beyond a specified threshold distance from the critical feature as unsuitable for breeding (score > 5). This is accomplished by the equation:

New habitat score for pixel beyond threshold distance = (1/2 of original habitat score) + 5

Therefore, if a pixel of habitat beyond the threshold distance from a critical feature had an original habitat score of 1 (optimal habitat), it receives a reclassified score of 5.5 (usable, but not breeding habitat). Likewise, unsuitable habitat located outside of the threshold distance remains unsuitable: an original score of 9 is reclassified as 9.5. All pixels of habitat within the threshold distance of a critical feature maintain their original habitat score.

## **Identifying Potential Breeding Patches and Potential Population Cores**

The habitat suitability map provides scores for each pixel. The analyst needs to identify—both in the Habitat Blocks and in the Potential linkage area — areas of good habitat large enough to support reproduction. Specifically, the analyst needs to identify

- potential breeding patches: areas large enough to support a breeding unit (individual female with young, or a breeding pair) for one breeding season. Such patches could be important stepping-stones for species that are unlikely to cross a potential linkage area within a single lifetime.
- potential population cores: areas large enough to support a breeding population of the focal species for about 10 years.

To do so, first calculate the suitability of any pixel as the average habitat suitability in a neighborhood of pixels surrounding it (Figure 4). Calculate average habitat suitability within a 3x3-pixel neighborhood (0.81 ha) for less-mobile species, and within a 200-m radius (12.6 ha) for more-mobile species<sup>4</sup>. Thus each pixel has both a *pixel score* and a *neighborhood score*. Then join adjacent pixels of suitable habitat (pixels with neighborhood score < 5) into polygons that represented potential breeding patches or potential population cores. The minimum sizes for each patch type are specified by the biologists who provided scores for the habitat suitability model.

<sup>4</sup> An animal that moves over large areas for daily foraging perceives the landscape as composed of relatively large patches, because the animal readily moves through small swaths of unsuitable habitat in an otherwise favorable landscape (Vos et al. 2001). In contrast, a less-mobile mobile has a more patchy perception of its surroundings. Similarly, a small island of suitable habitat in an ocean of poor habitat will be of little use to an animal with large daily spatial requirements, but may be sufficient for the animal that requires little area.



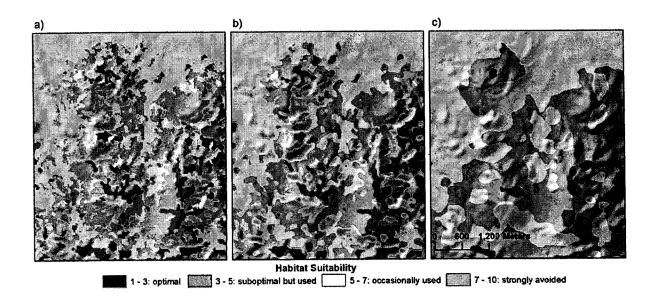


Figure 4: Example moving window analysis which calculates the average habitat suitability surrounding a pixel. a) original habitat suitability model, b) 3x3-pixel moving window, c) 200m radius moving window

## **Identifying Biologically Best Corridors**

The biologically best corridor<sup>5</sup> (BBC) is a continuous swath of land that is predicted to be the best (highest permeability, lowest cost of travel) route for a species to travel from a potential population core in one protected habitat block to a potential population core in the other protected habitat block. Travel cost increases in areas where the focal species experiences poor nutrition or lack of suitable cover. Permeability is simply the opposite of travel cost, such that a perfectly permeable landscape would have a travel cost at or near zero.

Develop BBCs only for some focal species, namely species that (a) exist in both protected habitat blocks, or have historically existed in both and could be restored to them, (b) can move between protected blocks in less time than disturbances such as fire or climate change will make the current vegetation map obsolete, (c) move near the ground through the vegetation layer (rather than flying, swimming, or being carried by the wind), and (d) have habitat preferences that can reasonably be represented using GIS

<sup>5</sup> This approach has often been called Least Cost Corridor Analysis (Beier et al. 2006) because it identifies areas that require the least cost of travel (energetic cost, risk of mortality) to the animal. However, the words "least cost" are easily misunderstood as referring to the dollar cost of conserving land or building an underpass.

variables. For focal species that did not meet these criteria, conduct patch configuration analysis (next section).

To define the start and end points for a corridor, identify potential population cores and habitat patches that fall completely within each protected habitat block. If potential population cores exist within each block, use these potential cores as the starting & ending points for the corridor analysis. Otherwise, the start-end points should be potential habitat patches within the protected habitat block or (for a wide-ranging species with no potential habit patch entirely within a habitat block) any suitable habitat within the protected block.

To create each biologically best corridor, use the habitat suitability score as an estimate of the cost of movement through the pixel6. Use these three rules to transform habitat suitability scores into travel costs, depending on ecological characteristics of the species:

• For a *locally widespread species* (habitat suitability score < 5 in nearly all of the potential linkage zone, suggesting that breeding populations could occur throughout), use the raw pixel habitat suitability score as the travel cost score.

Assign species not widespread throughout the potential linkage area into 1 of 2 groups:

- For corridor-dwelling species (species needing weeks to generations to traverse the potential linkage area including most reptiles, amphibians, and small mammals)7, reassign a score of 1 to each pixel in a potential habitat patch or potential population core. The rationale is that these areas provide steppingstones for multi-generational movement. Do not rescore single pixels, or polygons smaller than a potential breeding area, because these are too small to provide meaningful stopover habitat.
- For passage species (mobile species that can make the journey between protected habitat blocks in a single movement event of a few hours or days), assign each pixel with a pixel habitat suitability score of 1 through 5 a travel cost score of 1. In models that lacked this rescoring, the biologically best corridor tended to follow an unrealistic straight line rather than best habitat.

For each pixel, calculate the lowest cumulative cost to that pixel from a starting point in one protected habitat block. Similarly calculate the lowest cumulative travel cost from the 2<sup>nd</sup> protected habitat block, and add these 2 travel costs to calculate the *total travel cost* for each pixel. The total travel cost thus reflects the lowest possible cost associated with a path between habitat blocks that passes through the pixel.

<sup>6</sup> Levey et al. (2005) provide evidence that animals make movement decisions based on habitat suitability. 7 Beier & Loe (1992) introduced this distinction between *passage species* and *corridor-dwelling* species.





Finally, define the biologically best corridor as the swath of pixels with the lowest total travel cost and a minimum width of 500 m (Figure 5). If a species has two or more distinct strands in its biologically best corridor, eliminate any strand markedly worse than the best strand, but retain multiple strands if they have roughly equal travel cost and spacing among habitat patches.

After developing a biologically best corridor for each species, combine biologically best corridors to form a union of biologically best corridors (UBBC).

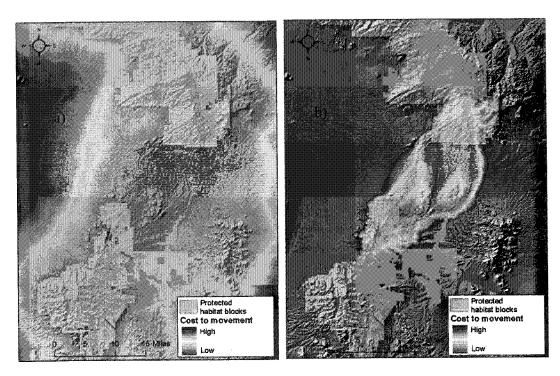


Figure 5: a) Landscape permeability layer for entire landscape, b) biologically best corridor composed of most permeable 10% of landscape.

#### **Patch Configuration Analysis**

Although the UBBC identifies an optimum corridor between the protected habitat blocks, this optimum might be poor for a species with little suitable habitat in the potential linkage area. Furthermore, corridor analyses were not conducted for some focal species (see 2<sup>nd</sup> paragraph of previous section). To address these issues, examine the maps of potential population cores and potential habitat patches for each focal species (including species for which a BBC was estimated) in relation to the UBBC. For each species, examine whether the UBBC encompasses adequate potential habitat patches and potential habitat cores, and compare the distance between neighboring habitat patches to the

dispersal<sup>8</sup> distance of the species. For those species (corridor-dwellers, above) that require multiple generations to move between protected habitat blocks, a patch of habitat beyond dispersal distance will not promote movement. For such species, look for potential habitat patches within the potential linkage area but outside of the UBBC. When such patches are within the species' dispersal distance from patches within the UBBC or a habitat block, add these polygons to the UBBC to create a preliminary linkage design.

#### Minimum Linkage Width

Wide linkages are beneficial for several reasons outlined above. To address these concerns, establish a minimum width of 1.5 km (0.94 mi) along the length of each terrestrial branch of the preliminary linkage design, except where existing urbanization precludes such widening. Widen bottlenecks first by adding natural habitats, and then by adding agricultural lands if no natural areas are available.

It is especially important that the linkage will be useful in the face of climate change. Climate change scientists unanimously agree that average temperatures will rise 2 to 6.4 C over pre-industrial levels by 2100, and that extreme climate events (droughts and storms) will become more common (Millennium Ecosystem Assessment 2005). Although it is less clear whether rainfall will increase or decrease in any location, there can be no doubt that the vegetation map in 2050 and 2100 will be significantly different than the map of current vegetation used in today's analyses. Implementing a corridor design narrowly conforming to current distribution of vegetation types would be risky. Therefore, in widening terrestrial linkage strands, attempt to maximize local diversity of aspect, slope, and elevation to provide a better chance that the linkage will have most vegetation types well-distributed along its length during the coming decades of climate change. Because of the diversity of focal species used to develop the UBBC, the preliminary linkage design will probably have great of topographic diversity, and minimal widening will be needed.

Expanding the linkage to this minimum width produces the final linkage design.

#### **Field Investigations**

Although these analyses consider human land use and roads, the GIS layers only crudely reflect important barriers that are only a pixel or two in width, such as freeways, canals, and major fences. Therefore visit each linkage design area to assess such barriers and identify restoration opportunities. Document areas of interest using GPS, photography, and field notes. Evaluate existing bridges, underpasses, overpasses, and culverts along highways as potential structures for animals to cross the highway, or as locations where improved crossing structures could be built. Note recent (unmapped) housing & residential developments, major fences and artificial night lighting that could impede

<sup>8</sup> Dispersal distance is how far an animal moves from its birthplace to its adult home range. We used dispersal distances reported by the species expert, or in published literature. In some cases, we used dispersal distance for a closely-related species.





animal movement, and opportunities to restore native vegetation degraded by human disturbance or exotic plant species.

# Helping Non-scientists Understand the Biological Value of Alternative Corridor Designs

The Linkage Design above provides a biological optimum. Various practical constraints will often require deviation from this biologically optimum design. During implementation of corridor designs, a diverse group of stakeholders must consider and compare alternative designs. Agencies making conservation investments prefer to buy large parcels from willing sellers, and developers will propose alternative corridor designs that do not affect their lands.

These alternative maps will differ from the biological optimum. How can decision-makers compare alternatives to the optimum, and know when to settle for "good enough"? The GIS analyst can calculate cost-distance for each alternative. But unfortunately, a 20% increase in cost-distance does not necessarily correspond to a 20% increase in animal mortality or a 20% decrease in gene flow. In other words, cost-distance is not a useful metric for comparison. Instead, we suggest histograms (e.g., of bottleneck lengths, bottleneck widths) and other metrics (e.g., average habitat suitability scores for each focal species, distances between suitable habitat patches within the linkage) to illustrate differences among alternative corridor designs. South Coast Wildlands and Arizona Wildlife Linkage Workgroup are currently developing such metrics and testing them on focal audiences.

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